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Magnetotail Structures in a Simulated Earth's Magnetosphere

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Abstract

Structure of the magnetotail is investigated in a laboratory simulated magnetosphere. Particular emphasis is placed on the region of distant magnetotail where the closed field line region of the plasma sheet terminates and the process of reconnection takes place. Our study builds upon the previous investigation of the magnetotail *(Birn et al. 1992)* where the main results were based on the magnetic field measurements in the tail region of the simulated magnetosphere. In this paper, more elaborate measurements of plasma flow and electric field are presented. Besides these measurements, this region of distant magnetotail is also explored by high resolution imaging with a gated optical imager (GOI) and the digital image analysis. These images clearly reveal a Y-type magnetic neutral line for the northward "interplanetary" field (IMF) and a usual X-type for the southward IMF that confirms our previous results deduced from the magnetic field measurements. In the neighborhood of these neutral points a strong component of dawn to dusk electric field (E_y) and a counterstreaming plasma flow is also observed. Plasma flow is measured by using a double sided Faraday cup which is also used to measure the y-component of tail current (J_y) at different locations. These measurements reveal that the tail current is not carried by ions as previously thought, rather it is carried by electrons alone.

1. Introduction

There has been a great deal of interest in the space physics community to understand the structure of earth's magnetotail under varying conditions of the solar wind plasma and its associated IMF. Both in situ observations and computer modelling has been used in the past to understand its structure and its variations imposed by external changes. The region of distant neutral line where the region of closed plasma sheet terminates and probable reconnection of magnetic field lines occurs is one of the most interesting and poorly understood region as far as the in situ observations are concerned. Until recently, it was explored only by one satellite ISEE 3 that was basically launched to monitor the solar wind parameters. In order to obtain the global features of this region with respect to the varying conditions of the solar wind plasma, a coordinated multi-satellite system is required. Therefore, we approach this problem by modelling the entire system of magnetosphere in laboratory by interacting a magnetized plasma flow with a dipole magnetic field. Our previous paper *(Birn et al., 1992)* presented the magnetic field measurements and numerical modelling of the tail region with particular emphasis on the distant neutral line. The main results of that study was the identification of a Y-type magnetic neutral line for the northward IMF and an X-type neutral line for the southward IMF. Those results strongly support the occurance of high-latitude night side reconnection, as suggested by *Dungey[1963]* for northward IMF and more recently by *Gosling et al. [1991]*.

In the present paper we are again concentrating in the same region and present further measurements of electric field and plasma flow for different polarities of the IMF. Also the global images of the simulated magnetosphere together with the detail digitization of the distant tail region are presented. In section 2 we will present these images and the global modelling of the magnetosphere. The plasma flow and electric field measurements will be presented in section 3. Section 5 will provide the conclusion of this paper.

2. Simulation Procedure and Imaging

The details of the experimental set up is presented in some of our previous papers *(Rahman, el.al,1991; 1989; Birn et al, 1992)*. The simulation is performed by interacting an intense magnetized plasma beam produced by a large plasma gun with a strong dipole field to form a magnetosphere that scales to the Earth's magnetosphere. The plasma and other parameters are presented in Table 1. The dimensionless parameters clearly show a better agreements with the MHD scaling requirements (*Rahman et. al, 1991)* except that the ratio of ion-Larmour radius with the size of the magnetosphere (r_{iL}/x_o) satisfies only marginally.

In the past, images were taken by using an open shutter camera. Light emitted from the hot plasma or from the background low density neutral gas molecules provides a source for these images. Variation in the light intensity develops due to the diverse plasma condition that exist in the magnetosphere. For example the bow shock, magnetopause boundary, neutral sheet, reconnection regions, plasma entry regions in the polar cusp and auroral formation regions at the poles are relatively brighter than the usual background. Since the density of the simulated solar wind plasma is $\sim 10^{13}\ cm^{-3}$, the strong light emitted by the brightest regions overexpose the film and a high resolution image cannot be obtained by simple open shutter technique. Therefore, the images taken by an open shutter camera show only limited features like magnetopause boundary, near earth neutral sheet and the auroral regions. The structures like bow shock, reconnection regions and the distant magnetotail could not be identified from those images.

The gated optical imager (GOI) provides a unique capability to obtain high resolution and also the dynamic behavior of the magnetosphere. Figure 1 shows the schematic diagram of GOI which is used to obtain these images. Light emitted from the magnetosphere is focused on a biased cathode that emits electrons. These electrons are accelerated by applying a square pulse of few micro-second duration, which is much shorter than the entire plasma pulse of 100 μsec, and then passed through a microchannel plate where the electron flux is amplified because of the secondary emission by almost a million times. This secondary electron flux is energized by applying a high voltage of 6-7 kV which can reconstruct the magnetospheric image on a phosphorus screen that is finally photographed on an ordinary film. Using this technique we were able to image for the first time, the detailed structures of the bow shock and the distant magnetotail. These images can be further enhanced by using a CCD camera and computer aided digitizing techniques. In this way not only the qualitative informations but also some quantitative information can be extracted from this imaging technique.

Fig. 2 represents a sample image of a laboratory magnetosphere for the southward polarity of IMF with an applied strength of 200 G. The magnetic field that penetrates into the plasma is always less than 100 G with an insignificant reduction in the plasma flow speed (*Wessel et al. 1990*). Therefore the Alfvén Mach number is almost 2 for all these images. The exposure time of this image is 5μsec. A series of images taken during the entire interaction period have shown that this type of global structure persists 80% of the interaction time. Plasma entry from the polar cusp, formation of bow shock, elongated magnetotail and auroral formation can be clearly identified in this image. An extended X-type neutral line can be clearly seen in the current sheet of the magnetotail that persists up 40μsecs. The lower panel of Fig. 2 is digitized version of the distant neutral line region that shows more clearly the formation of the X-type reconnection in the tail region that corresponds exactly the same position where the neutral line was predicted from the magnetic field measurements. This image reveals the presence of a hot trapped plasma between the earth and the neutral line region and a hot flaring plasma away from the neutral line. Figures 4 presents the image for the northward IMF with 200 G applied magnetic field. In this image, a clear separation of bow shock and magnetospause is not very obvious, however, this image clearly reveals an open magnetosphere. An extended neutral sheet in the tail region is also very obvious that have a strong resemblance with the predicted Y-type magnetic neutral line. The region is further clarified in the digitized version presented in the lower panel which seems to be again consistent with our previous measurements of the magnetic field (*Birn et al., 1992).* The complete dynamic evolution of the laboratory magnet is presented in a separate paper *(Yur et al., 1993).*

3. Plasma Flow and Electric Field Measurements

To measure the plasma flow and identify different boundaries of the simulated magnetosphere, a new type of double sided Faraday cup is developed. The schematic of this Faraday cup is shown in Fig. 4 which has a dimensions of 1 cm^3. This combination of two Faraday cups can measure simultaneously the counter streaming fluxes of either ions or electrons. For this paper we used this probe to measure the ion flux (en_iv_i) at various regions of the tail. Fig. 5 presents the ion flux J_i versus z at $x = 9.75$cm behind the model earth for the southward IMF of 200 and 300 G. This location is in the closed field region and in the vicinity of the termination point. Significantly enhanced plasma fluxes, both earthward and tailward, near the equatorial plane are quite obvious from these measurements. The tailward ion flux is almost twice as large as the earthward ion flux. The flux profile has a symmetrical behavior in both upper and lower lobes. Fig. 6 is the same data at $x = 6.75$cm, much closer to the model earth, but only in the upper lobe. In this case the flux in both direction has almost the same magnitude. This data implies the presence of a trapped hot plasma with temperature of 50-100 eV in the near earth tail region. Fig. 7 and 8 are the similar flux profiles for the northward IMF again at 6.75 cm and 9.75 cm respectively. Again the pattern is similar to the southward IMF case except that now the net flux is somewhat smaller in magnitude. This implies that the net plasma density in the case of northward IMF is lower than the southward IMF case which may be due to the reduced level of entry from solar wind to the magnetosphere for the northward IMF. The trapped plasma seems to have entered from the neutral point in the distant tail region that can also be seen from the images presented in Fig. 2 and 3. We have also used this diagnostic to measure the fluxes along the y-axis that show almost the same level of flux in both directions, which may be an indication that the tail current is mainly carried by electrons. Using a double Langmuir probe we have also seen a significant enhancement in plasma density and temperature in the regions of enhanced ion fluxes. These measurements represent the first identification of plasma sheet and lobe region s through plasma data in the simulated magnetotail.

The presence of the energized plasma in the photographic pictures possibly indicates the effects of a localized electric field, which favors a dynamic picture. For this purpose we performed some measurements of E_y as function of x along the tail axis. For this purpose a floating E-probe is used, the circuit diagram of which is given in Fig. 9. For southward IMF of 200 and 300 gauss, the E_y as a function of x is presented in Fig. 10. This figure shows that E_y is concentrated in the vicinity of the neutral point, having a double peak structure. Fig. 11 shows E_y as a function of x for northward IMF. In this case only a single flat peak appears with E_y gradually approaching zero as we move the probe away from the model earth. The most interesting feature is that this E-field does not correspond to the $\mathbf{v} \times \mathbf{B}$.

4. Conclusions

In conclusion we have studied the structure and dynamics of the magnetotail in a laboratory magnetosphere. The images taken by the GOP show that a quasi-stationary magnetosphere develops in less than 2 μsecs and persists for almost 50 μsecs without any substantial variation in the global structures that is comparable to the total duration of the plasma flow which is 70-100 μsecs. Global features like bow shock, magnetopause boundary, plasma sheet in magnototail, reconnection region, auroral regions, plasma entry regions etc. are first time clearly identified. For the southward IMF a usual X-type neutral line region in the distant magnetotail can be easily identified from these images. On the other hand, for the northward IMF a long plasma sheet originating from the model earth is observed which is an indication of a Y-type magnetic neutral line. These results are consistent with our previous magnetic field measurements in the tail region of the model magnetosphere (*Birn et al.1992)*. Detailed measurements of plasma flux, electric and magnetic field, and other plasma parameters support these observations.

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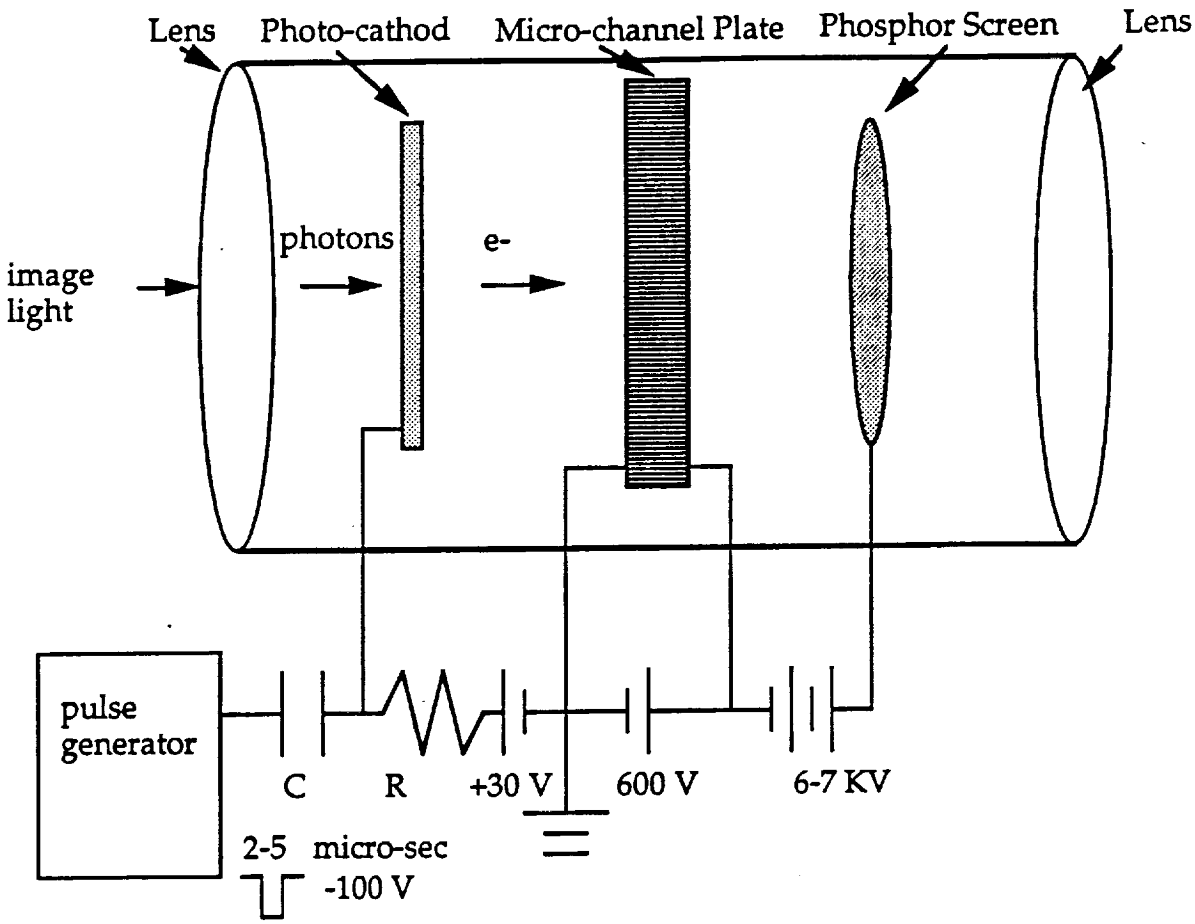

Fig. 1 Schematic of the gated optical imager (GOI)

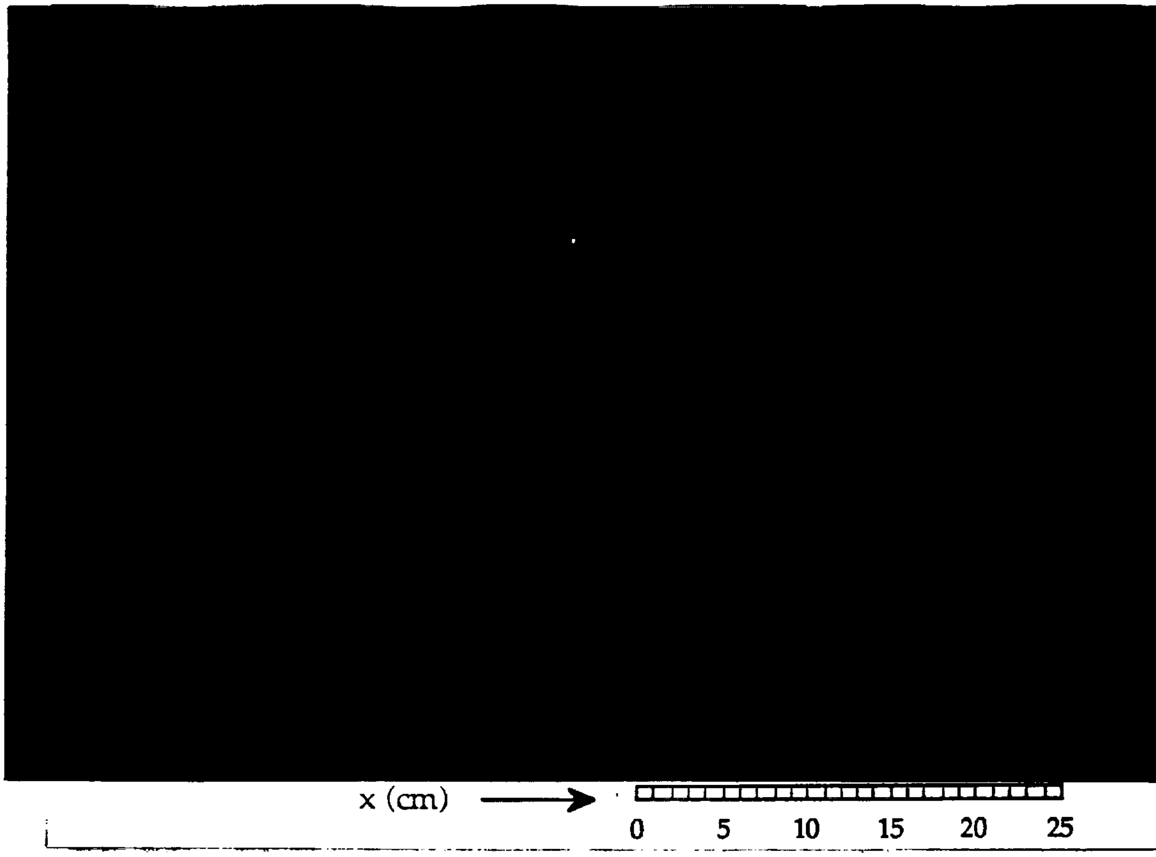

Fig.2A Photograph taken by GOI for 200 G of southward IMF. The duration of the exposure is 5 μsec.

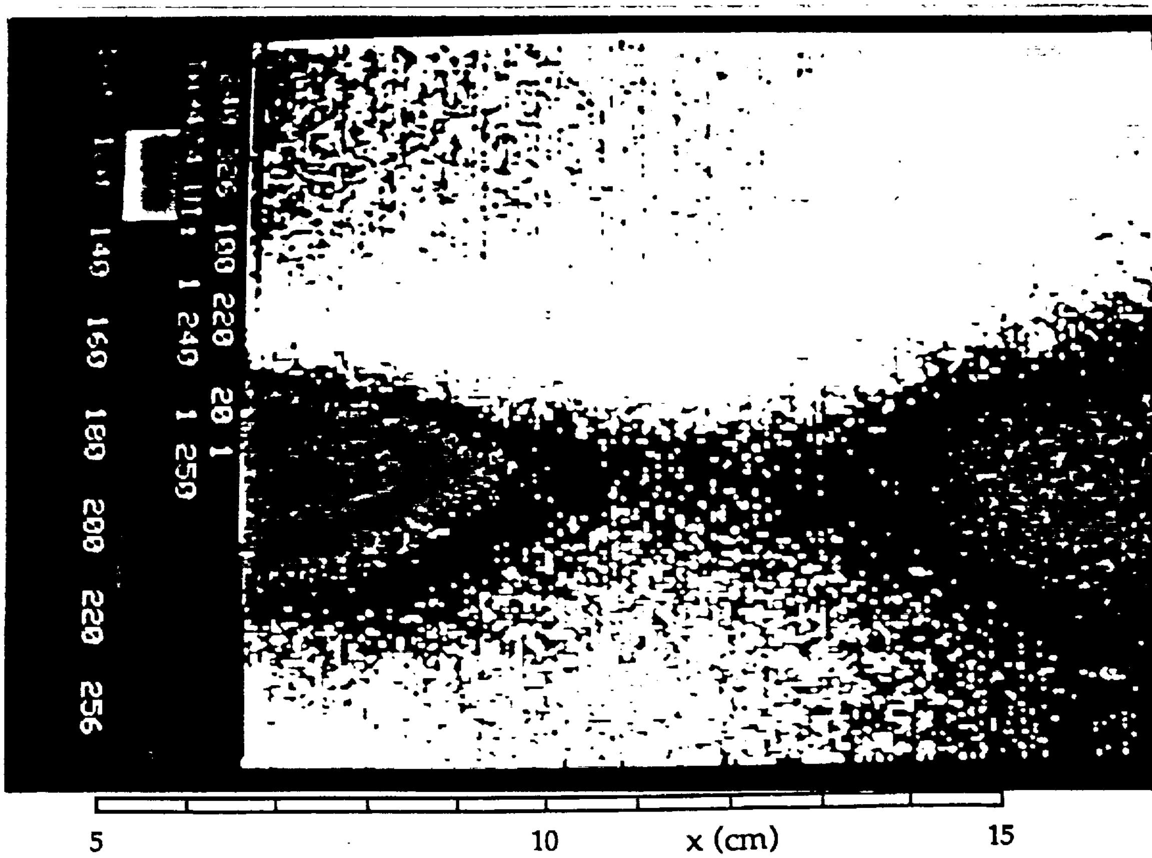

Fig.2b Digitized image of the photograph taken by GOI for 200 G of southward IMF. The duration of the exposure is 5 μsec. It shows the x-type reconnection of the tail region.

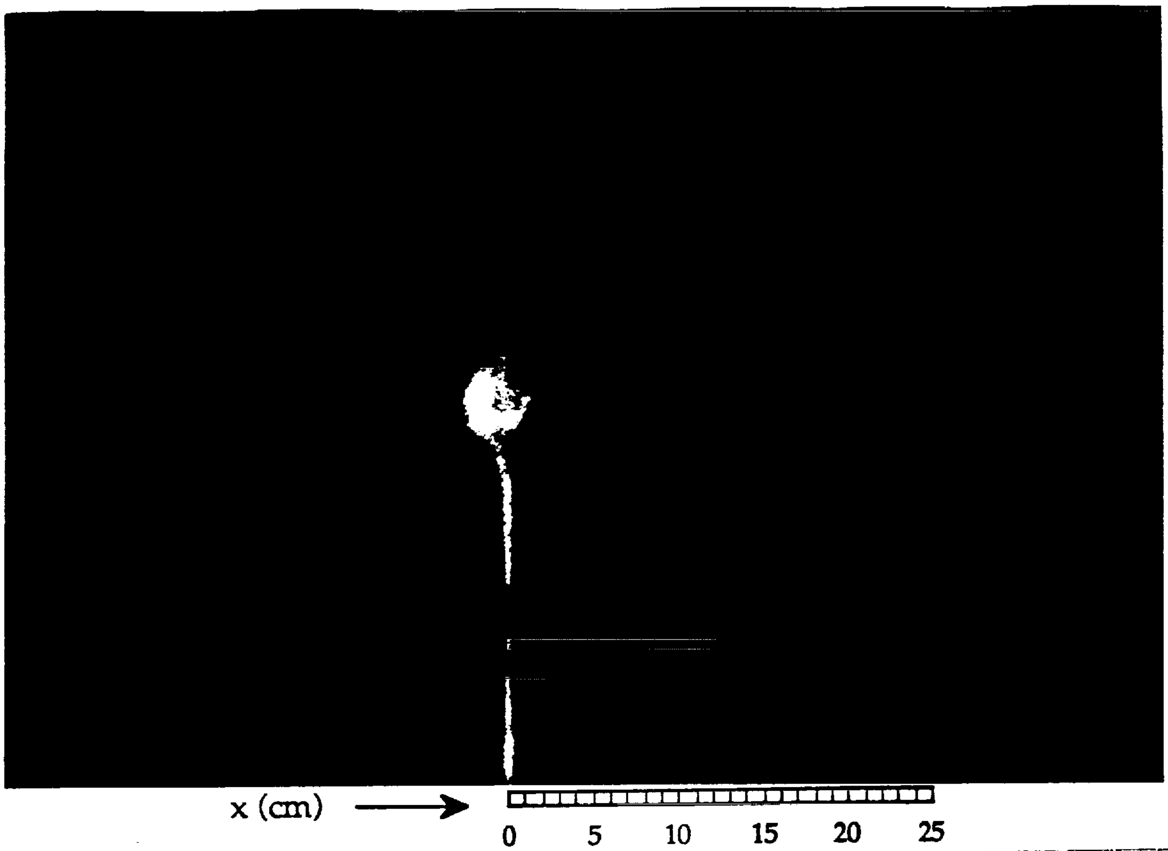

Fig.3a Photograph taken by GOI for 200 G of northward IMF. The duration of the exposure is 2 μsec.

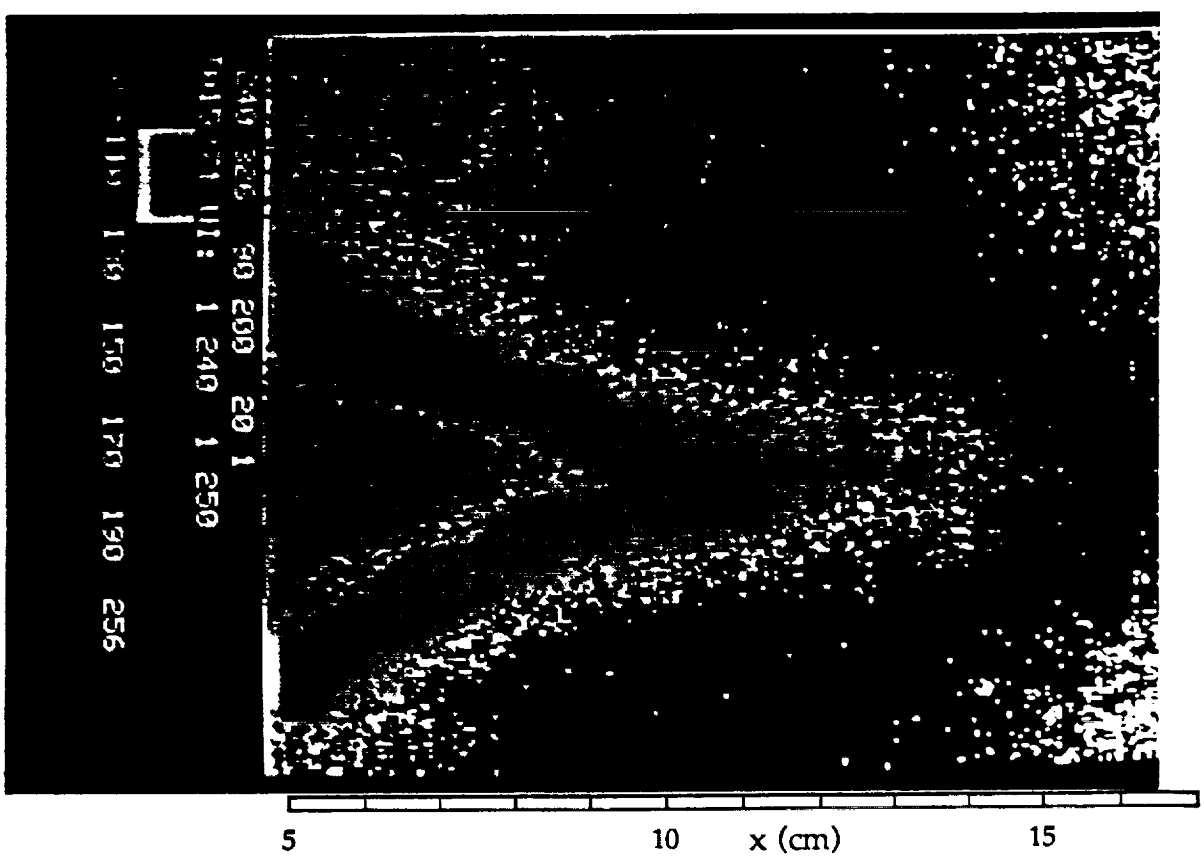

Fig.3b Digitized image of the photograph taken by GOI for 200 G of northward IMF. The duration of the exposure is 2 μsec. It shows the y-type reconnection of the tail region.

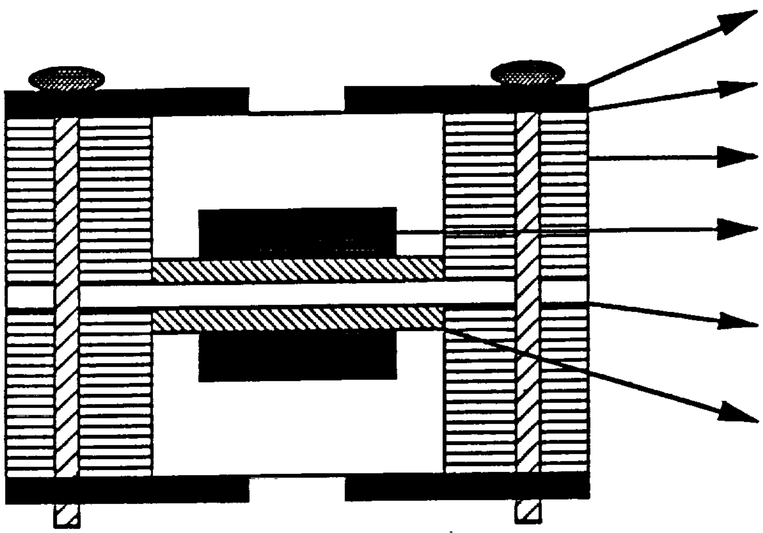

Fig . 4 . Schematic of a double faraday cup used to measure both forward and backward flow simultaneously.

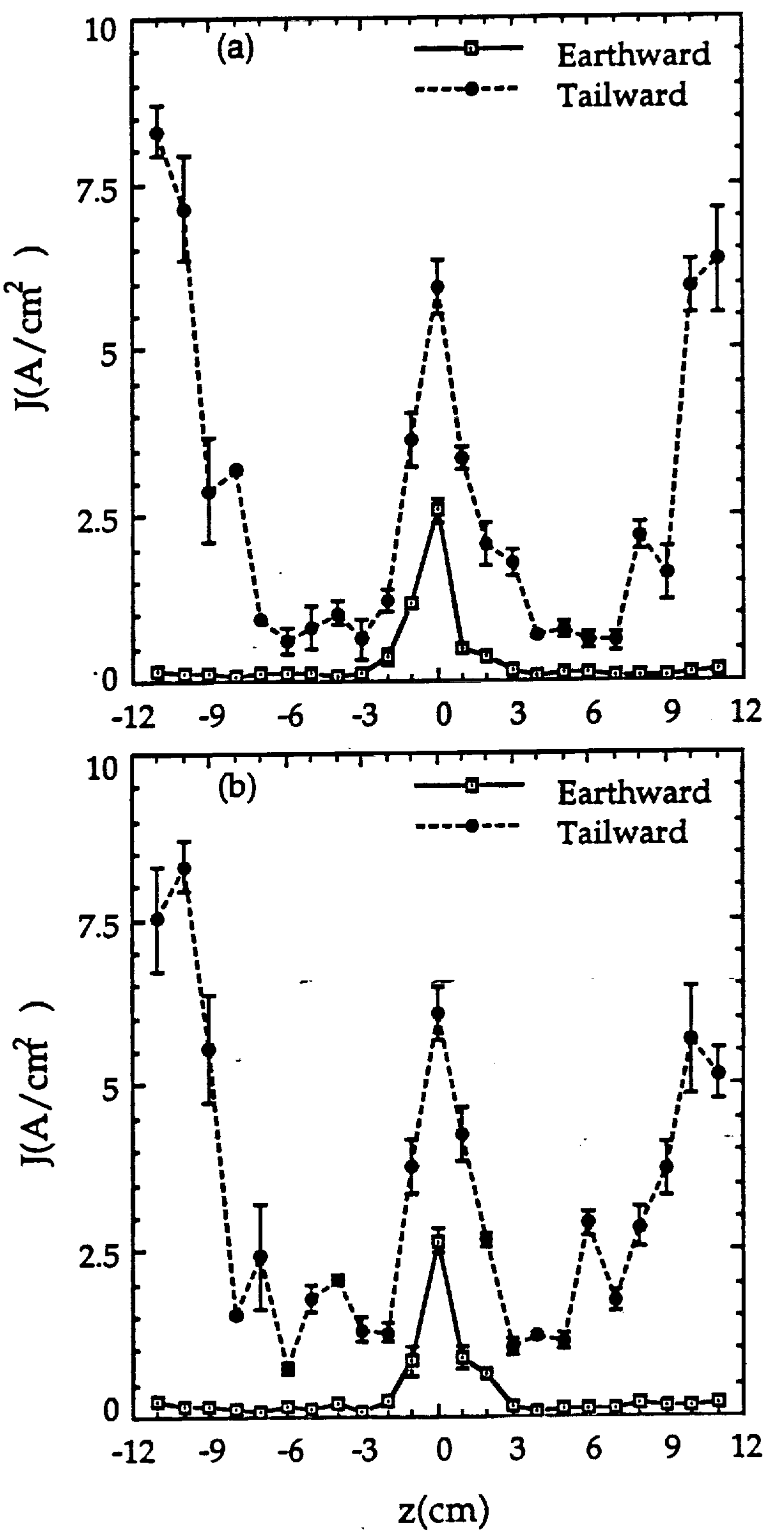

Fig. 5. Ion flux as function of z measured by a double sided Faraday cup at x=9.75 cm in the tail region for southward IMF, (a) B=-200G, (b) B=-300G.

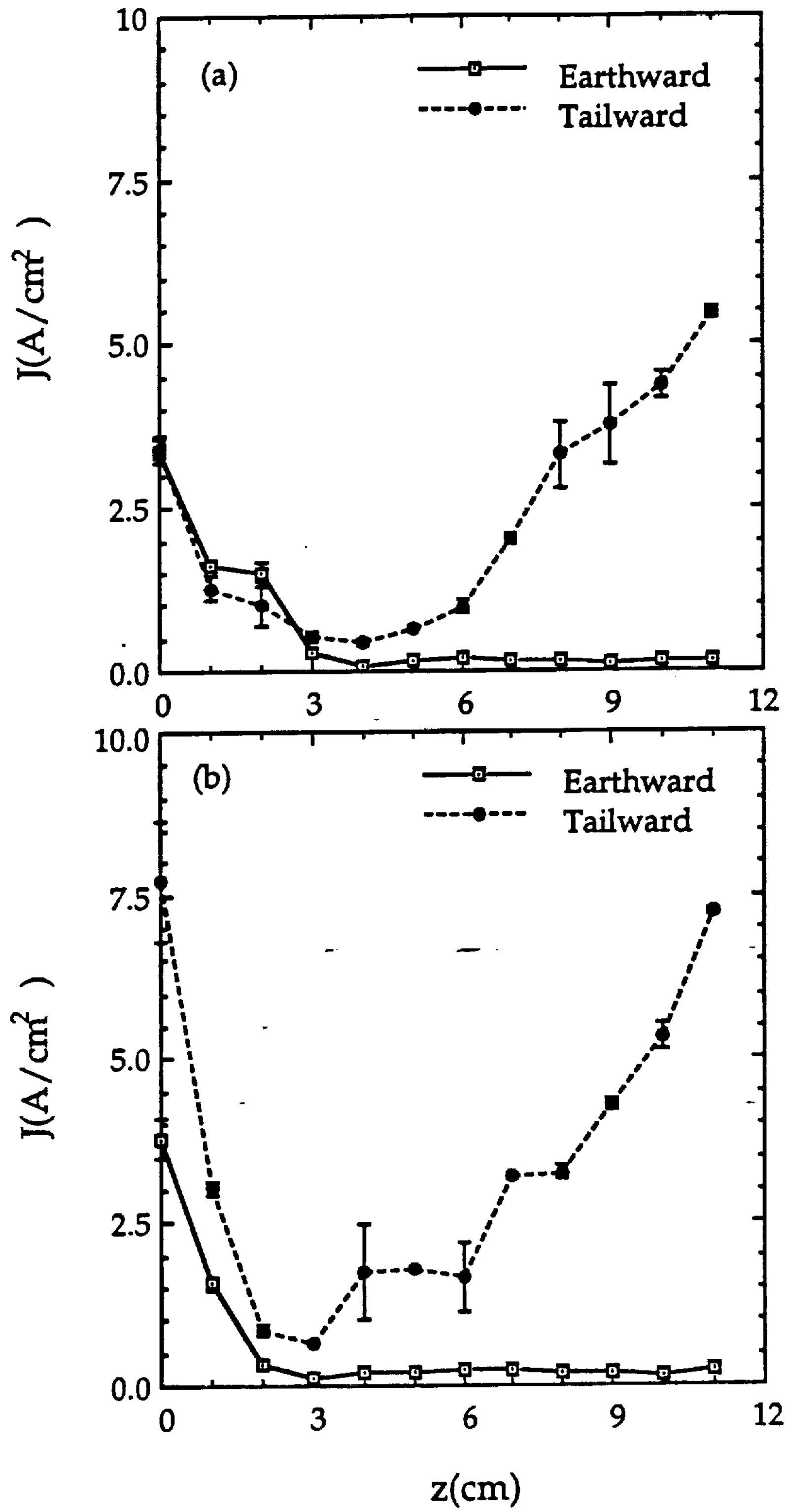

Fig. 6. Ion flux as function of z measured by a double sided Faraday cup at x=6.75 cm in the tail region for southward IMF, (a) B=-200G, (b) B=-300G.

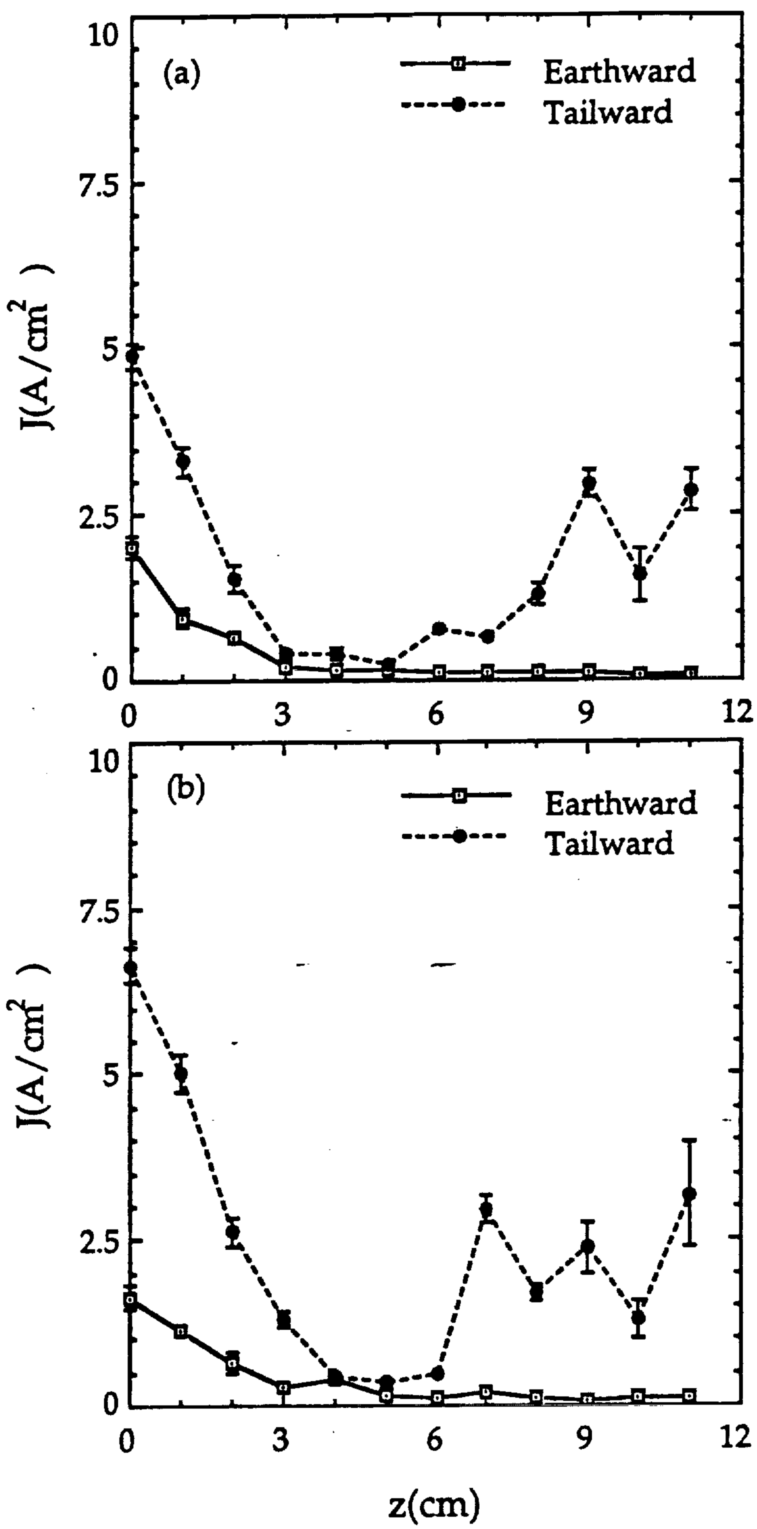

Fig. 7. Ion flux as function of z measured by a double sided Faraday cup at x=9.75 cm in the tail region for northward IMF, (a) B=200G, (b) B=300G.

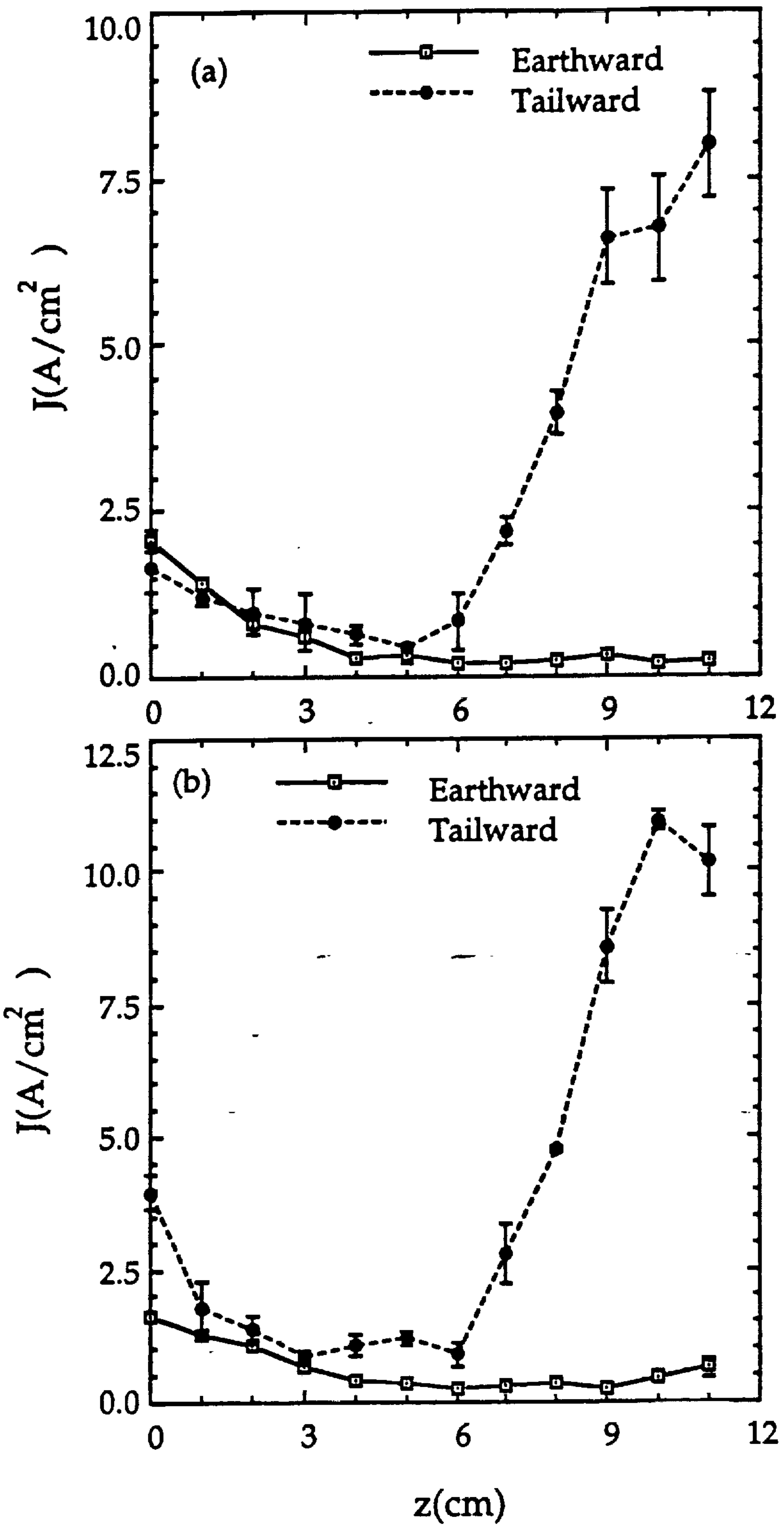

Fig. 8. Ion flux as function of z measured by a double sided Faraday cup at x=6.75 cm in the tail region for northward IMF, (a) B=200G, (b) B=300G.

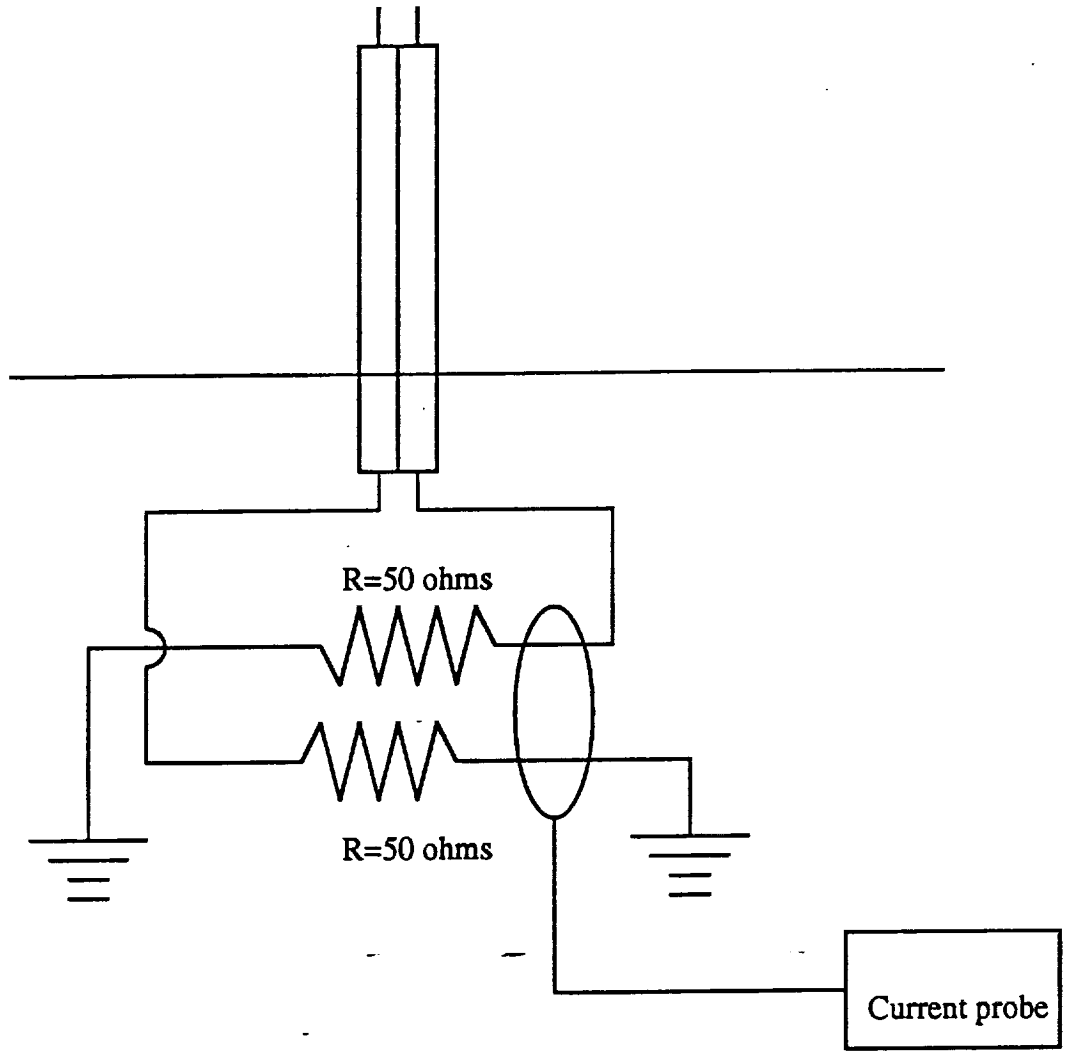

Fig. 9 Schematic of the E-probe.

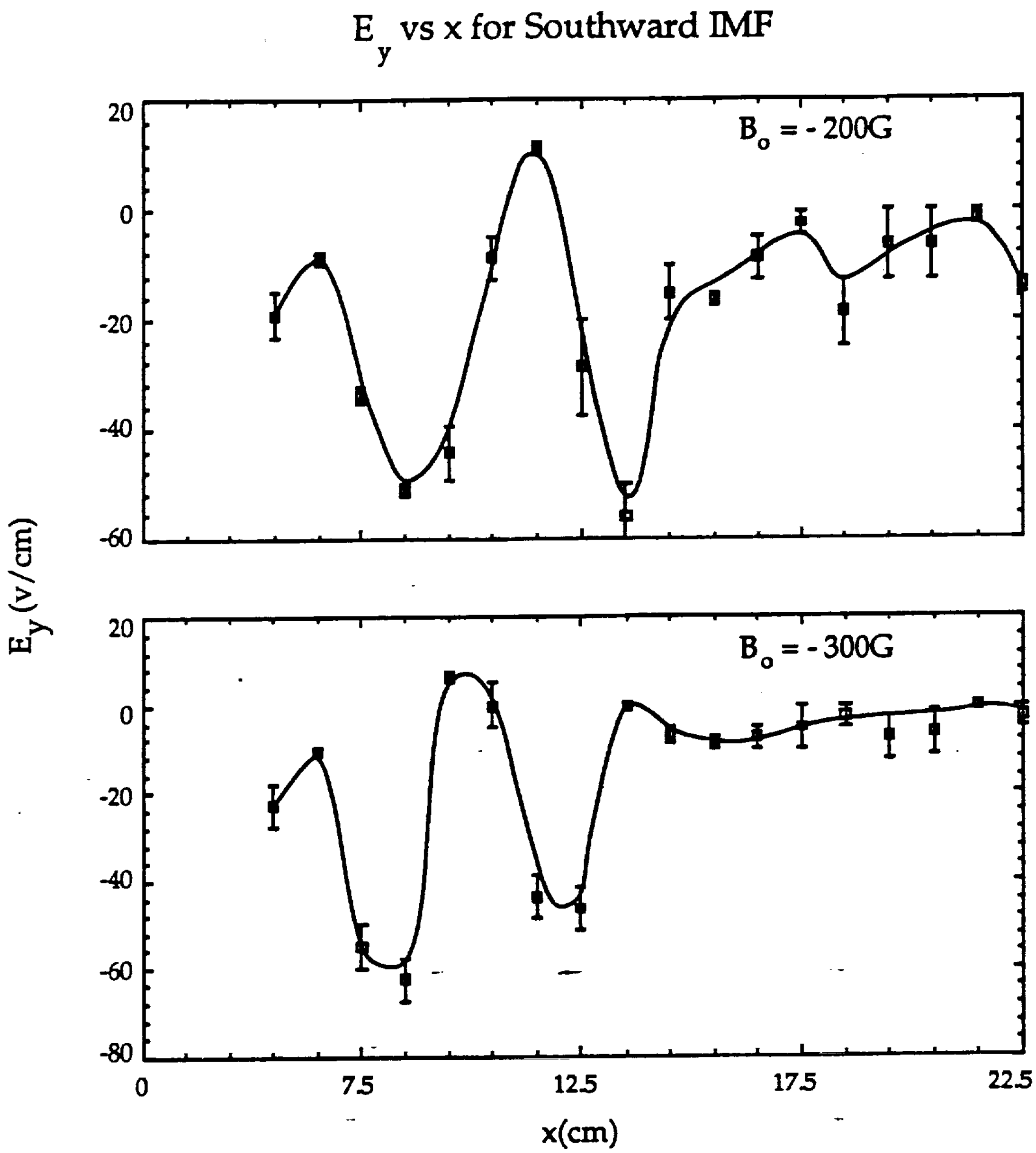

Fig. 10 Y-component of the electric field is plotted along the x-axis for the southward polarity of IMF. The electric field is seen to have two strong componants around the neutral point.

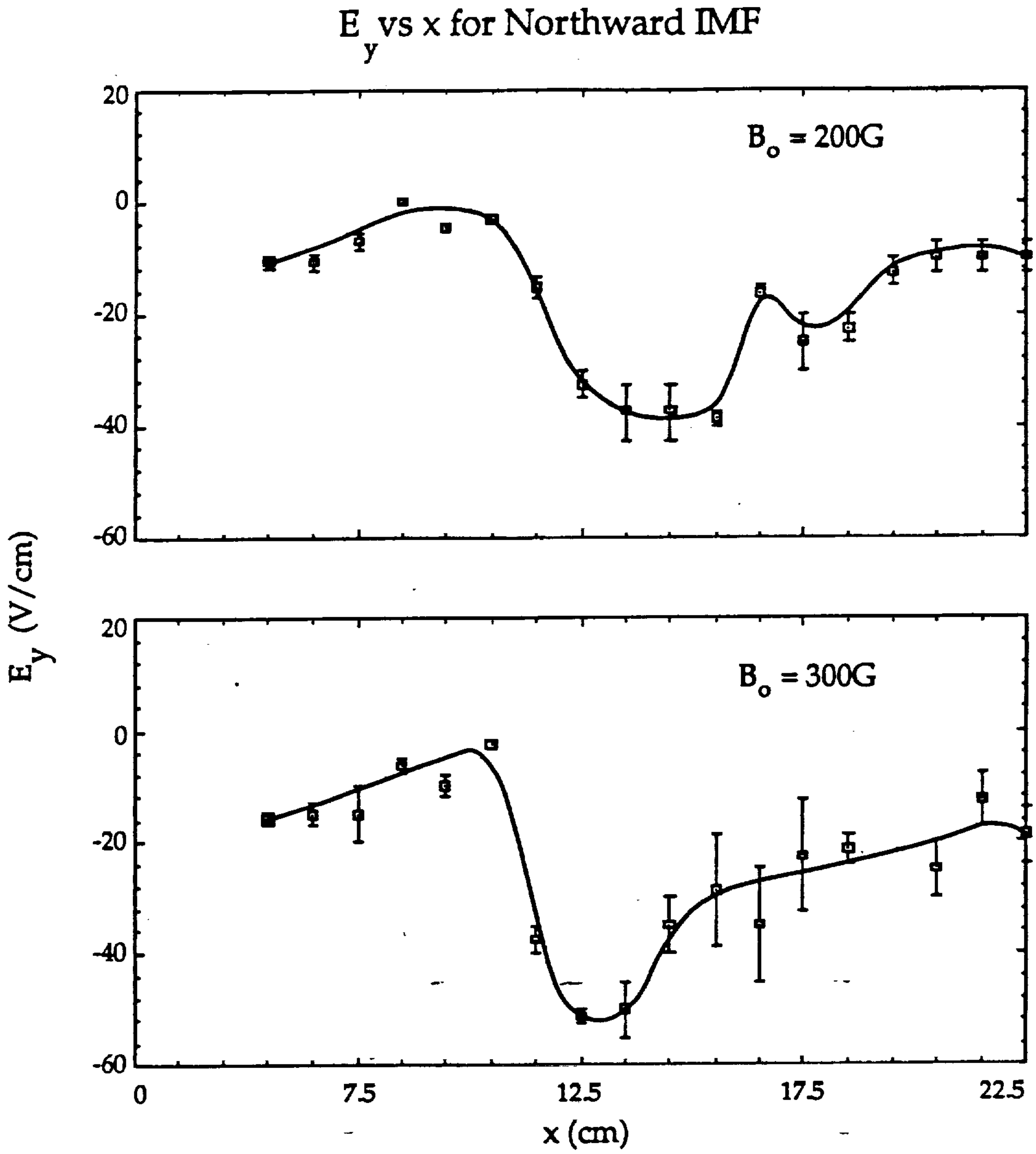

Fig. 11 Y-component of the electric field is plotted along the x-axis for the northward polarity of IMF. The electric field is seen to have a strong componant around the neutral point.